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SYNOPSIS: In the area of "AKTEA", a summer-housing estate 36 Km away from the city of Athens, a great landslide affected the stability of a semi-bridge, constructed in 1980 for the widening of the nearby national road. Preliminary studies carried out before the semi-bridge construction and after the observed damage of most of the houses in the uphill area, favoured the existence of a very superficial creep affecting however the one or two storey buildings of the summer-housing estate.

After the semi-bridge construction, instability phenomena continued in an increasing rate and a more systematic geotechnical investigation revealed definite landslide movements (instead of a superficial creep) in a depth 2.5 to 4.0 metres below the foundation level of the piers of the semi-bridge and in a depth 6-8 m below the road level. This paper describes details of the above landslide, the investigations carried out and the remedial measures suggested.

INTRODUCTION

The national road from Athens to Sounion, 68 Km long is of paramount importance since it is the main coastal road connecting the city of Athens (Greece) with the archeological site of Sounion passing through a series of coastal boroughs, and some of the most picturesque bays of Greece (inset to Figure 1). Serious slope instability problems have been observed between the 35 and 37 Km on this road. In particular the road and the nearby summer-housing estate of "AKTEA" located in the 36th Km have been affected by a major landslide. This housing estate was built in 1972-74 in a hilly region (40-60 meters above sea level) and in an average distance of about 160 metres from the nearby coast. The national road passes downhill from the housing estate of "AKTEA", in an elevation of about 25 metres, separating the above estate from the coastal area (Figure 1). The slope inclination varies between 15°- 18°, although locally much greater values can be observed. The slide has been active with intermittent movement for more than 30 years. It began to gather interest in the late 1960's as the summer-housing estate of Aktea was going to be founded and the old national road to be widened.

Before the estate was built a visual reconnaissance conducted by Kotzias and Stamatopoulos (1970) revealed some characteristic features of instability in the uphill region of the road, such as scarps on the ground and disturbed trees with obvious bends in their trunks. After the completion of the buildings construction some rather severe damages were noted (Figure 2) and another study was conducted by Muller (1976) which included borings (depth up to 40 metres), shafts(1.5 m diameter and up to 25 m deep) and a survey for levelling and measurement of horizontal displacements of slope surface. The results of this study led to the conclusion that the slope movement of "AKTEA" was a creep phenomenon (with a rate of displacement varying from 0.1 to 0.4 mm/day)

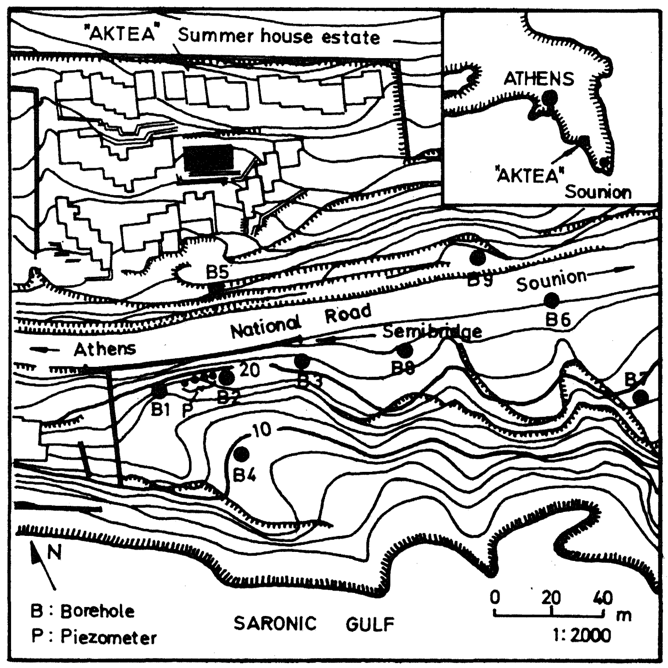

Fig. 1 Plan View of Slide Area

affecting the whole area of the estate which covers a surface of about 12000m².

It must be noted that such sliding phenomena are easily noticeable in adjacent areas and very close to the national road as can be seen in Figure 3 where damaged and abandoned buildings due to landsliding are shown.

Later, in 1980, in order to widen the national road in this region and after taking into account

Fig. 2 Tilting of a Retaining Wall inside the "AKTEA" Estate

Fig. 3 Damaged Buildings due to Landsliding

the creep phenomena observed, it was decided that the best solution to the problem was by a semi-bridge construction. The piers of this bridge were founded on the sound rock and in a depth below the unstable superficial creep zone.

GEOLOGICAL SETTING

The broader area of "AKTEA" consists mainly of neogene lacustrine deposits, of a thickness more than 100 metres, overlying the bedrock of Triassic marble. These deposits include alternating layers of conglomerates and clayey or sandy marls with lenses or thin intercalations of sandstones. The conglomerates are well cemented and polymictic with a prominent joint set almost vertical to the bedding. The marls, brownish yellow or greyish coloured, are fissured and often laminated, and present characteristic polished surfaces with striations (slickensides). The intense microfolding and microfaulting of these marls result locally in a variation of the dip of the strata which generally is opposite to the dip of the natural slope (dip direction of strata 10°-30°ENE).

The geological reconnaissance of some outcrops near the coast and of large excavations for building foundation close to the studied area, revealed characteristic features of synsedimentary faulting and slumping which disturbed the original structure of these deposits. Furthermore, a surficial zone of varying thickness (2 to more than 5 metres) was observed in which a rather great disturbance of rocks had taken place in the past probably due to a hillside instability which occurred during Pleistocene or even earlier. Interpretation of old aerial photographs taken before the "AKTEA" housing estate was built, showed typical characteristic features of active landsides such as scarps on the hillside and vegetation disturbance.

Finally, regarding the underground water conditions, the existence of a permanent water table is unlikely, since the water percolating the surficial zone flows through the strata of conglomerates and away from the slope. The percolation of underground water results, during wet seasons, in the moistening of the interlayers of the marls but probably without any pore pressure development.

PROBLEMS RELATED TO THE SEMI-BRIDGE CONSTRUCTION

The semi-bridge which was constructed for the road widening had a total length of about 60 metres and 12 spans with the sections of the roadway slab freely supported (Figures 4 and 5). During the excavation for the foundation construction the slope beside the working space was nearly vertical and without any temporary covering or support.

The rising piers have been backfilled to a new working level about three metres under the level of the existing road. The cross section of the rising piers was 0.8 X 0.8 square metres with a

Fig. 4 View of the Semi-bridge and of "AKTEA" Summer-housing Estate

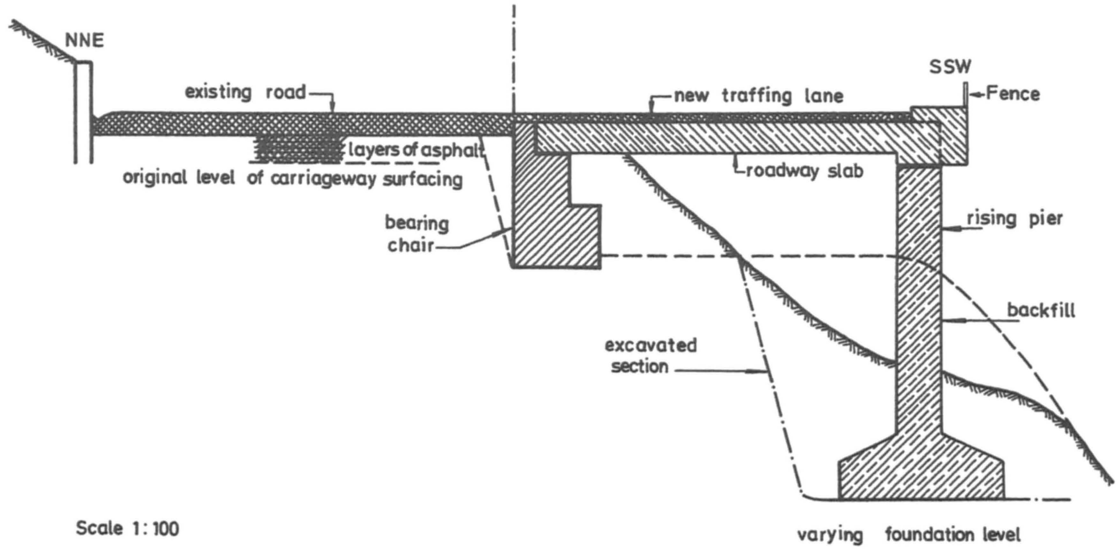

Fig. 5 Cross-section of the Semi-bridge and Details of Excavation and Backfilling

height of about seven metres. The construction of the piers was made in sections in order to avoid any risk of slope failure uphill from the semi-bridge. At that time the depth of the foundation level was considered to be satisfactory and in any case greater than the depth of the superficial creep.

A strip foundation (bearing chair) was constructed along the middle-line of the new road at an elevation of about three metres below the level of the existing road (Figure 5). The whole structure included also two wing-walls founded at about the same level as the piers.

However, two years after the completion of the semi-bridge construction some cracks appeared in the road-pavement and a rather large inclination of the wing-wall of the bridge was observed as it is illustrated in Figure 6. In addition a gradual loss of alignment of the piers and an offset increasing with time was observed as it is clearly shown in Figure 7. These phenomena continued in an increasing rate and an extensive investigation program was planned and carried out in order to have a better understanding of the cause of these movements and propose some remedial measures to solve the whole problem.

Fig. 6 Wing-Wall Tilting and Repaired Road Pavement

Fig. 7 Loss of Alignment of the Piers of the Semi-bridge

FIELD AND LABORATORY INVESTIGATIONS

In the narrow area of the semi-bridge, nine borings (Figure 1) were carried out in order to identify the subsurface geology, to obtain samples for laboratory testing and to install inclinometer tubes for determining the depth and shape of probable slides. Installation of four open standpipe piezometers at one single location for monitoring the underground water level was also considered necessary, even if the surface reconnaissance and previous investigations showed that ground water table was almost at sea level.

Finally, a surface surveying was carried out to monitor movements of the ground surface, to determine the extent of landslide activity and the rate of movement. For this purpose the slope of "AKTEA" has been covered by benchmarks and transit stations located on stable ground and a net of hubs for which subsequent movements could be determined.

Drilling of boreholes and installation of inclinometers and piezometers was carried out in January - February of 1985 and monitoring started in March 1985 and ended in May 1987 because of the distortion of the tubes due to sliding. The surface surveying started in the summer of 1986 and is still in progress.

RESULTS AND DISCUSSION

In Figure 8 a typical soil profile is shown based on the logging of borehole B2. As is shown in this Figure the narrow area of the semi-bridge consists of alternating layers of conglomerate, sandstone and marl, whereas the upper 1 - 2 metres consist of fill material. The thickness of the well cemented, polymictic conglomerate is about 3 metres. The sandstone is friable and marly or well cemented and its thickness varies from 3 to 4 metres. The marl is hard in greater depths and presents some slickensided surfaces. The SPT

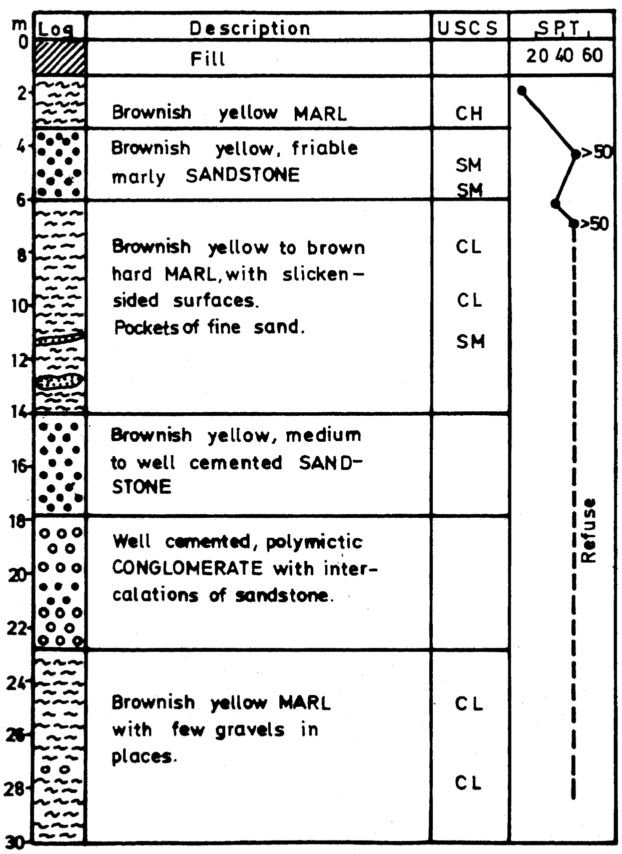

Fig. 8 Typical Soil Profile

values for the surficial layers of marl range between 10 and 30 whereas in greater depths these marls present a refuse to SPT sampler penetration.

Atterberg limit determinations on samples of marls obtained from borings, showed that most of material can be classified as CL (low to medium plasticity clays) or CH (high plasticity clays), whereas samples of friable sandstone or pockets of sand can be classified as SM (silty sand).

As it was impossible to take undisturbed samples of marl, because this was very hard and the use of thin wall samplers prohibitive, laborarory testing was restricted only to the estimation of its residual shear strength characteristics, by using the ring shear apparatus (Bromhead, 1979). The residual shear strength characteristics of marl, as found in this apparatus using remolded material with a water content approximately at the plastic limit, was $c_r' = 0$ and $\phi_r' = 14° - 16°$. These values are very low considering other marls of various sites in Greece, (Tsiambaos, 1987), but this can be explained by the low calcium carbonate content of "AKTEA" marls (< 20%) as it was determined by chemical analyses.

Regarding the location of underground water level, the open standpipes showed no evidence of water above the sea level. It must be noted that for an accurate exploration of the underground water level the four standpipe piezometers were installed close, to each other and had different lengths. Their perforated sections were at different levels so that they covered totally a depth up to 25 metres. In this way any groundwater level (free or perched) could be easily detected.

The data from the inclinometers B1, B2, B3 demonstrated conclusively that slope failure was occurring along a surface 2.5 to 4.0 metres below the foundation level of the piers of the semi-bridge and in a depth 6 - 8 m below the road level. Analyses of the inclinometer B4 data installed downhill from the semi-bridge showed the existence of a slide in a depth of 8m while data from inclinometer B5 installed uphill from the semi-bridge (Figure 1) located the slide surface in a depth of approximately 5.8 m. The mean rate of movements (total horizontal displacements) was very low, locally varying between 0.6 and 2.0 cm/year, whereas the movement direction was N5°W to N25°E, towards the coast. The movement rate varied seasonally, being greatest in spring and early summer and least during fall and winter.

Figure 9 shows the angular variation and the resulted horizontal displacement for inclinometer B2 during the period 18.4.1985 and 19.2.1987, whereas in Figure 10 the total horizontal dispacement (N6°E direction) with time, is illustrated. The data from the inclinometers B6, B8 and B9, installed eastern from the semi-bridge (Figure 1) showed the same type of sliding as above in a depth of about 7.5 - 8.5 m below the surface of the new road. On the contrary, inclinometer B7 showed no evidence of sliding and so it could be considered that the location of this inclinometer is out of the limit of the observed landslide. Surface surveying which is still in progress showed a definite horizontal displacement of slope surface only in the narrow area of B6, B8 and B9 inclinometers and also a differential movement of the wing-walls of the semi-bridge.

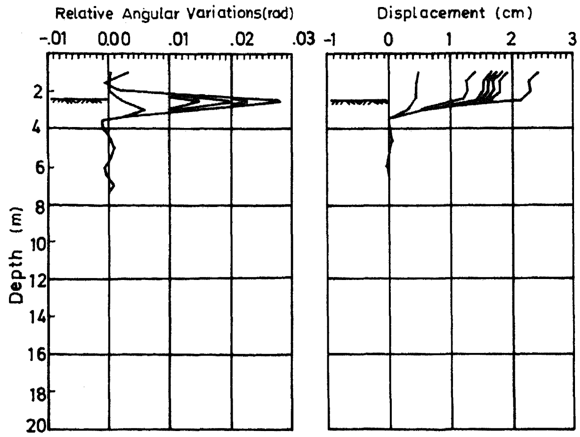

Fig. 9 Movement of Inclinometer B2

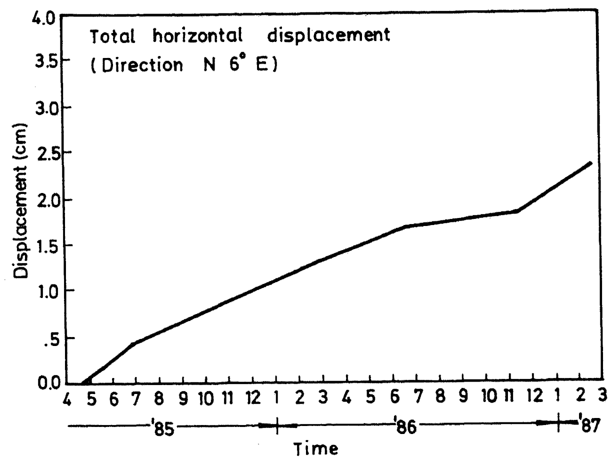

Fig. 10 Total Horizontal Displacement of Inclinometer B2 with Time

On the basis of the geological data, the logs of boreholes and inclinometers data, the geological cross section across the inclinometers B5, B2 and B4, of a direction NNE to SSW, was able to be drawn as it is illustrated in Figure 11. As is shown in this Figure the slip surface is a rather undulating one which crosses the marl layers as well as the layers of conglomerates and sandstones. It must be noted that sliding takes place through the mass of marls, but the sliding surface follows the joints and cracks of conglomerates and sandstones which are mainly subjected to extension and not to shearing. It is believed that the structure of the conglomerates and sandstones above the sliding surface has been disturbed due probably to an old landslide.

The landslide seems to extend under the bottom of

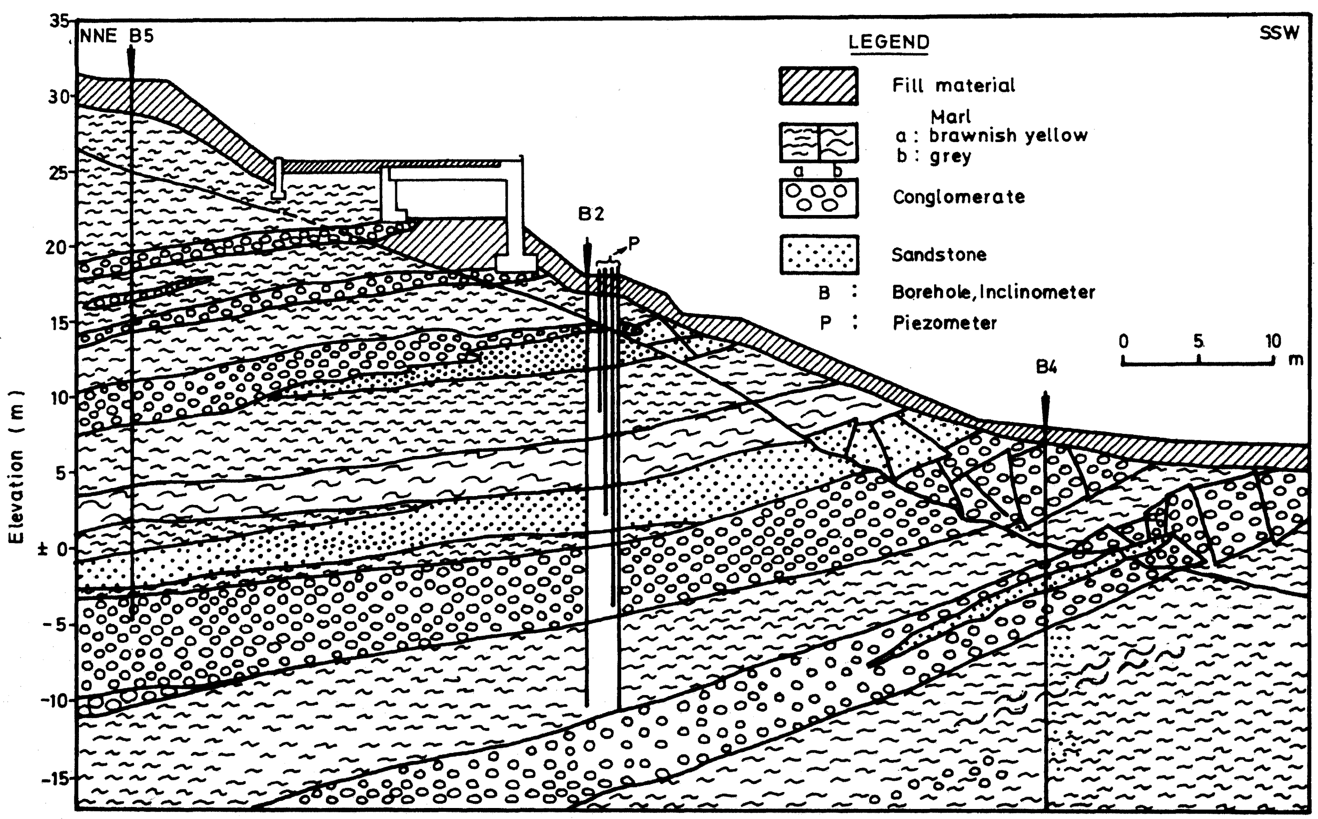

Fig. 11 Geological Cross Section and Location of Slip Surface

The landslide seems to extend under the bottom of the sea and in a remarkable distance from the coast line. Evidence to support this, are some characteristic geomorphological features on the bottom of the sea such as long open cracks and ridges which are easily observed under favorable weather conditions.

Janbu (1973) and Morgenstern and Price (1965) methods of slope stability analysis were used to analyze the slip surface assuming the sliding mass to be in a state of limiting equilibrium and a piezometric grade line coincident with the sea level. Drained strength parameters of $\phi' = 14°-15°$, $c' = 0$ were backfigured as the average strength acting on the slip surface producing a safety factor of unity. It must be noted that the sections analyzed were slope configurations with : a) the crest of the landslide located in the uphill area (inside the housing estate) where the main scarps are easily noticeable, and the toe close to the semi-bridge and b) the same location for the crest of the landslide but with toe located at the sea bottom and at a distance from the coast line which is found following the curvature of the slip surface drawn in Figure 11.

The average soil strength parameters estimated from the above slope analyses were very close to the residual shear strength parameters of the marly soil confirming that : a) the landslide occurring in this area is an old one but still active and b) the major part of the length of the slip surface passes through the mass of the layers of marls.

It is well known that some actual or potential slides can be stabilized by means of piles (piers) driven or bored into stable underlying soil. In the case of the semi-bridge considered in this article, it is expected that a drilled cantilever pier wall downhill from the semi-bridge to stabilize the slope, has the advantage of being installed without significantly decreasing slope stability during its construction. In addition such a construction seems to be particularly advantageous in that it may be constructed with the minimum of excavation. It has been observed that, excavation downhill from the national road and adjacent to the area of the semi-bridge for foundation construction of a villa resulted in a large instability of the uphill region and in severe cracks of the national road pavement. Considering that, in urban areas such "AKTEA" the rights-of-way are restricted, the authors favoured and adopted the solution of a drilled cantilever pier wall suitably instrumented for future monitoring together with a series of subsidiary measures which are now under design.

CONCLUSIONS

The conclusions that may be made from the case history concerning the behaviour and performance of the semi-bridge and analyses described in the article are as follows:

- the existence and implications of the old landslide in the area of "AKTEA" were not recognized almost 20 years ago when the works for building the summer-housing estate were designed and constructed.
- visual reconnaissance and incomplete field studies could not approach the real situation and the landslide was considered as a superficial creep.
- the monitoring of the mass movements showed definite but very slow landsliding in a depth of 6 - 8 m below the road level and 2.5 to 4.0 m below the foundation level of the piers affecting the overall stability of the semi-bridge.
- the residual shear strength parameters of marly soils obtained from laboratory testing were representative of the actual in situ mobilized strength of the soils involved and subjected to continous landsliding.
- since, the national road from Athens to Sounion is of a great importance, the stabilization of the landslide in "AKTEA" area is an indispensable work to be done. The solution of the construction of a pier wall downhill from the semi-bridge seems to be attractive and together with some secondary remedial mesures has been adopted and is now under design.

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